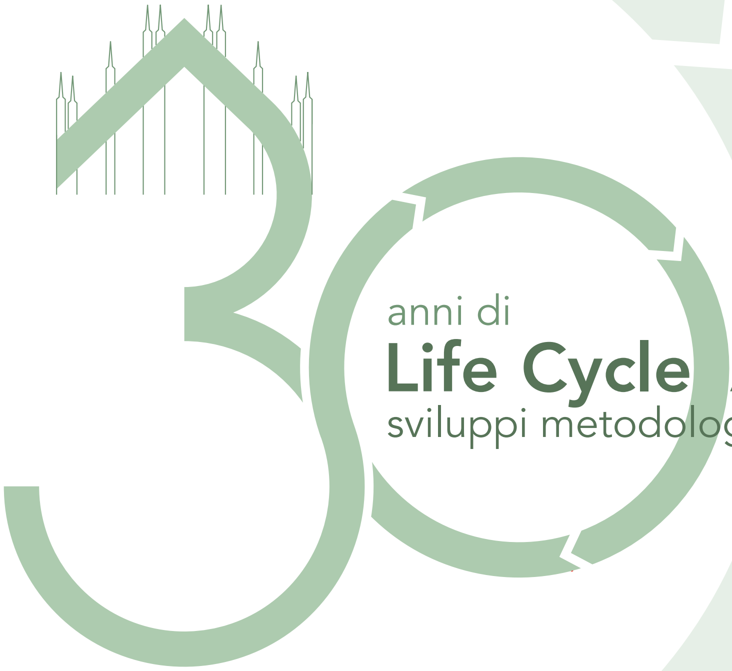

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Life Cycle Assessment

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XVII Convegno della Associazione Rete Italiana LCA

28-30 giugno 2023

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ATTI DEL CONVEGNO

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Carbon accounting of bio-based materials for construction in LCA analysis: A scientific literature review

Fernanda Speciale[1], Francesco Pittau[1], Laura Elisabetta Malighetti[1], Monica Lavagna[1]

Abstract: The construction sector has a significant impact on the environment, as it contributes to resource depletion, greenhouse gas emissions, and waste generation, but also has the potential to promote sustainability through the use of environmentally-friendly materials and technologies. The use of bio-based materials in buildings is growing due to increased demand for sustainable alternatives to traditional synthetic products, and also for their CO_2 storage capacity. The paper deals with how biogenic carbon accounting of buildings and construction products is assessed in LCA, through a study based on European standards and a literature review.

1. Introduction and Background

Climate change arising from anthropogenic activity has been identified as one of the greatest challenges posing significant questions for governments, businesses, and individuals, with far-reaching consequences for both natural and human systems. To address this issue, initiatives are being developed at the international, regional, national, and local levels to limit greenhouse gas (GHG) concentrations in the Earth's atmosphere. Such GHG initiatives rely on the assessment, monitoring, reporting, and verification of GHG emissions and/or removals. IPCC has analyzed various scenarios for global warming and corresponding strategies to reduce emissions (IPCC, 2018). Based on this scientific evidence, policymakers have agreed to use the 2°C target as an important objective for international climate policy (UNFCCC, 2015).

The construction sector plays a significant role in the climate crisis, as it is responsible for 23% of global human-related GHG emissions (UN IEA, 2017). Unfortunately, this sector poses a challenge in decarbonization compared to other industrial compartments, requiring significant investments to transform its fossil fuel-dependent infrastructure and its interdependencies with other sectors such as energy and mobility. While past efforts focused on reducing building operational emissions through energy efficiency and renewable energy use (Lützkendorf et al., 2014; Passer et al., 2019), recent studies suggest that the emphasis should shift to other stages of the life cycle, such as embodied carbon associated with manufacturing, transport, and construction, to achieve complete decarbonization of construction (Drouilles et al., 2019; Mirabella et al., 2018; Röck et al., 2020). To this extent, the life cycle assessment (LCA) methodology is typically applied. In a building LCA, the environmental impacts are generally divided into operational and embodied impacts. The operational impacts are related to the operational energy and water use. Embodied

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impacts occur in all other life cycle stages and are related to material production, transport, end-of-life processing as well as maintenance, and replacements (CEN, 2011).

Meanwhile, it has been demonstrated that higher GHG concentration levels than those consistent with long-term temperature targets may be possible if negative emissions technologies, also called carbon capture and storage (CCS) reabsorb this concentration excess before 2100 (van Vuuren et al. 2013). For buildings, alternative solutions using local resources, such as earth, bio-based, and reused materials, are emerging globally and promoting regenerative outcomes by contributing to the restoration and improvement of natural and social environments (Pittau et al., 2022). Bio-based materials, particularly fast-growing ones like straw fibers, hemp, and flax, can effectively aid climate restoration by restoring carbon in the soil (Pittau et al., 2018). Nevertheless, their usage is not widespread in the construction industry due to their still relatively high cost and a lack of knowledge among decision-makers and practitioners. Moreover, the effect due to biogenic CO_2 storage and delayed emissions are not included in the standard methodology for carbon footprint calculation because of their need to take several variables into account.

2. Main issues on carbon accounting in LCA analysis

Using bio-based construction materials in buildings can offer a valuable opportunity to store carbon in the built environment (Churkina et al., 2020). Harvesting wood from the land and using it as a bio-based construction material instead of synthetics, allows the carbon embedded in the biomass to be stored for a long period in the building, rather than being emitted into the atmosphere as with biofuels. During this storage period, the carbon is slowly regenerated in the forest, contributing to negative emissions. While much of the carbon stored in bio-based construction products is emitted as CO_2 at the end of the building service life, the same amount of carbon can be assumed to be sequestered when the regrowth of trees is completed (Gustavsson and Sathre, 2006). As a result, bio-based construction products are generally considered "carbon neutral." However, the extent to which this carbon neutrality leads to climate neutrality is still questioned by several authors (Brandão et al., 2012; Cherubini, 2015; Negishi et al., 2019).

Using biomass for building construction affects multiple activity systems, including forestry and agriculture, the energy sector, the construction industry, and building and waste management, making it hard to not consider the effects of dynamics of biogenic carbon dioxide cycles. Several researchers have developed models and methods to assess these cycles including the benefits of delaying biogenic carbon emissions by storing carbon in buildings (Pittau et al., 2022). According to different standards, biogenic CO_2 must be explicitly stated in the EPD of building products, taking into account all stages of the product's life cycle, including end-of-life releases. However, a time-dependent recognized methodology for accounting for the evolution of environmental conditions over time and the interaction between the carbon stored in the biogenic product and the atmosphere is still lacking.

Moreover, the question of which system takes benefits (credits) from using biogenic materials in construction still needs to be definitively answered (Pittau et al., 2022). On one hand, forestry contributes to replenishing carbon in the land, with direct CO_2 uptake in the biomass and forest soils. It has been demonstrated that efficient and sustainable management of the forests, by means of cutting mature trees for the production of bio-based products, harvesting residues for energy production, and replanting young trees for afforestation and carbon uptake, can contribute to improving the carbon storage capacity in the biosphere (Eriksson et al., 2007). However, carbon restoration through forestry may not be effective if harvested carbon is not temporarily fixed in long-life products like buildings and building materials. The risk is to assign the same credits to both systems, resulting in dangerous double-counting and overestimation of carbon benefits from biogenic construction (Pittau et al., 2022).

Traditional LCA is a static approach that aggregates past, present, and future GHG emissions at time zero, without a time factor being applied to CF (Fenner et al., 2018). This can be problematic when examining biogenic materials as not all are equal, as demonstrated by Pittau et al. (2018). Bio-based products can have varying lifetimes, ranging from a matter of days or weeks to many decades or even centuries when properly designed and incorporated into buildings. In addition, to properly assess the impact of the use of biogenic products in construction, economic, political, and social aspects of the growing location and conditions must also be taken into account to consider the pace of exploitation of these resources.

3. Approaches in the standards and scientific literature

The ISO 14040, 14044, and 14067 standards provide an important framework for LCA and the calculation of the carbon footprint of a product (CFP). This framework, however, leaves the individual experts, practitioners, and data developers, with a range of important choices that can be individually interpreted. The CFP is determined by calculating greenhouse gas emissions and removals in a product system, represented as CO_2 equivalents, using the single impact category of climate change (ISO, 2018). According to standard EN 15804, the calculation of credits for biogenic carbon storage in buildings has to be considered in the LCA approach. However, nowadays ordinary LCA databases do not contain a specific section on CO_2 storage (Pittau et al., 2022). Consequently, the evaluation of biogenic carbon is a significant point of contention within LCA, with differences in opinion regarding its assessment (Levasseur et al. 2013; Breton et al. 2018).

When CO_2 is stored as carbon in a product for a specified time, this carbon storage shall be treated according to the provisions in 6.5.2 of ISO 14067. According to this standard, if any carbon storage in products is calculated, it shall be documented separately in the CFP study report but not included in the CFP. In the case of products from biomass, carbon storage is calculated as carbon removal during plant growth and subsequent emission if the carbon is released in the end-of-life stage. The carbon removal is equal to the carbon contained in the product (ISO, 2018). Biogenic carbon dioxide is emitted into the air as CO_2, CO, or CH_4 as a result of the oxidation and/or reduction of biomass by means of its transformation or degradation (e.g. combustion, digestion, composting, landfilling). On the other hand, biogenic carbon can also be captured as CO_2 from the atmosphere through photosynthesis during biomass growth, a process commonly considered carbon sequestration (Brandão et al. 2013). When biomass is used for building materials, the effects of dynamics of biogenic carbon dioxide cycles affect multiple activity systems: forestry and agriculture, the energy sector, the construction industry, building, and waste management. From the literature, it emerges how its inclusion in CFP for buildings is limited due to the omission of the time dependency of the cycles (emission-uptake) and their consequence on GWP (Pittau et al., 2022). Furthermore, there is a lack of information regarding the real service life of buildings and materials, and the treatment of materials at the end of their service life, which is typically unknown and difficult to predict at the time of installation.

The assessment of the environmental impact of such multi-output cascade systems is challenging due to the involvement of multiple products and recycling steps, as well as the distribution of emissions, especially biogenic CO_2, over long periods (Pittau et al., 2022). Therefore, it is crucial to conduct a transparent and comparable carbon footprint assessment of biogenic materials to prevent misleading information, especially when using long rotation species as construction material with a long service life (Lippke et al., 2011).

In the early 2000s, most LCA experts and practitioners adopted the "carbon neutral approach" to calculate biogenic carbon (Vogtländer et al., 2014). This approach assumes that the release of carbon from a biogenic product at the end of its life is neutralized by the absorption of carbon dioxide by its replacement via photosynthesis during forest growth. However, some LCA methods consider the impact of temporary carbon storage by including carbon sequestration as an option, such as the British Publicly Available Specification PAS 2050 2011, the GHG Protocol Product Standard of 2011, and the European Commission's International Reference Life Cycle Data System (ILCD) Handbook. In these standards, it is possible to give credit to temporary storage by discounting delayed emissions. However, Vogtlander et al. (2014) argue that this method leads to an overestimation of the benefits, as it only considers the uptake of biogenic carbon during production and disregards emissions from disposal or combustion at the product's end of life.

Traditional LCAs typically use two common methods to evaluate biogenic carbon removals and emissions: the 0/0 approach and the -1/+1 approach. The 0/0 approach, also known as the 'carbon neutral approach', assumes that the release of CO_2 from a bio-based product at the end of its life is balanced by an equivalent uptake of CO_2 during biomass growth. According to this approach, as the timing of emission removal is not included in the calculation and all GHG inputs are shifted at time zero, the carbon neutrality assumption leads automatically to a climate-neutrality. As a result, biogenic CO_2 uptake and release are not taken into account (0/0).

Instead, the -1/+1 approach, adopted for building products (EN 15804, 2019), tracks all biogenic carbon flows throughout the building's life cycle. This method considers both biogenic CO_2 uptake (-1) and emissions (+1), as well as the transfers of biogenic carbon between different systems. During forest growth, the uptake of biogenic CO_2 is transferred to the building system and reported as a negative emission during product and construction processes. At the end of the building's life, biogenic CO_2 (or CO or CH4) is released, or the carbon content is transferred to a subsequent product system in the case of recycling (Fig.1). In both cases, a positive emission is reported during the end-of-life stage. An important aspect of this approach is that the biogenic carbon balance should be zero for all product systems.

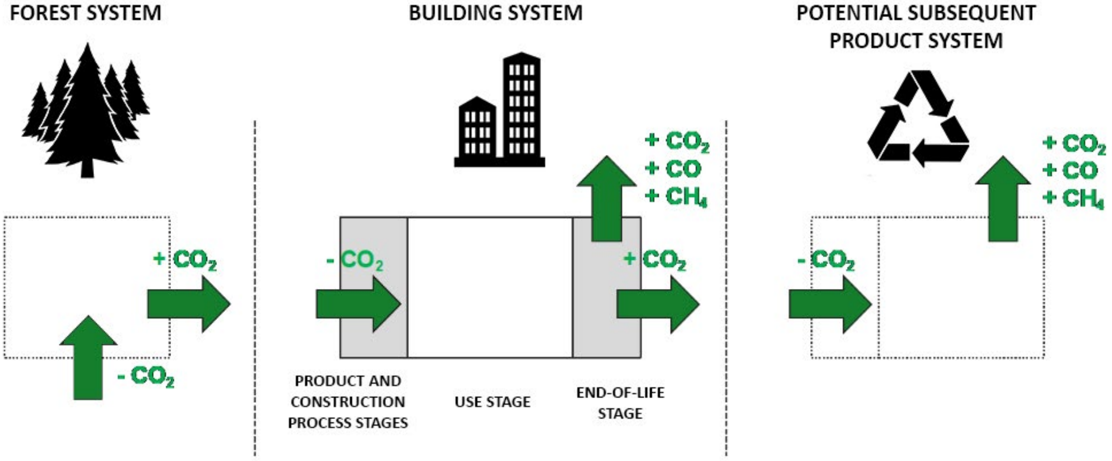

Figure 1. Scheme of –1/+1 approach. Dotted lines indicate the product systems that fall outside the system boundaries, source: Hoxha et al., 2020

Although the -1/+1 approach provides an overview of all biogenic carbon flows compared to the 0/0 approach, it still has limitations, such as not considering the time influence on global warming potential (GWP) and the risk of biased and misleading results when only assessing the impact of product and construction process stages without reporting the release of biogenic CO_2 at the end of life (Pittau et al., 2022).

The main criticism of traditional LCA approaches, as identified in the literature, is their failure to consider the timing of carbon emissions and the influence of different rotation periods related to biomass growth. This can be problematic when assessing the GHG impact of bio-based products in the construction sector. Additionally, studies like Pittau et al. (2018) demonstrate that not all bio-based products can be considered climate neutral, even if they are carbon neutral. For example, timber products that have been processed into beams or planks have a longer rotation period due to slow forest growth periods, making them unsuitable for carbon neutrality in a short time horizon. On the other hand, fast-growing bio-based materials, such as straw and hemp, have a short rotation period and can effectively mitigate GHG emissions by quickly removing carbon from the atmosphere (Pittau et al., 2018).

4. Review of semi-static and dynamic approaches

As previously mentioned, when biogenic materials are used in construction, emissions, and sequestration of biogenic CO_2 usually occur at very different points in time. However, in most LCA studies, the impact of these temporal effects on climate change is not considered. Biogenic CO_2 is either not taken into account, or emissions and uptake are assumed to balance out during biomass growth. To address this issue, various dynamic approaches to account for these temporal effects have emerged, starting with bioenergy (e.g. O'Hare et al., 2009; Kendall et al., 2009; Levasseur et al., 2010; Cherubini et al., 2011) and later bio-based materials (Guest et al., 2013; Levasseur et al., 2013). As already presented, the issue of biogenic carbon accounting has also been raised in several standards, such as ISO 14067:2018 and EN 15804:2019, Greenhouse Gas (GHG) Protocol (WRI and WBCSD, 2011), International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010), and Publicly Available Specifications (PAS) 2050 (BSI, 2011), which either prescribe a method or leave the approach to the user. Despite various approaches reported in the literature (Daystar et al., 2017; De Rosa et al., 2018; Levasseur et al., 2013), there is still a lack of consensus on the most appropriate methodologies for dynamic accounting of carbon flows in carbon footprinting and LCA studies.

Dynamic Life Cycle Assessment (DLCA) methods incorporate the impact of timing in environmental assessments, going beyond the carbon-neutral assumption. Levasseur et al. (2010) proposed a method using time-dependent characterization factors, while Cherubini et al. (2011) developed specific characterization factors for biogenic CO_2, which consider the rotation period of biomass. The longer the rotation period, the higher the biogenic global warming (GW) score due to the longer mean stay of CO_2 in the atmosphere. Guest et al. (2013) extended Cherubini et al.'s method to assess the impact of carbon storage in wooden products and found that carbon neutrality is achieved when stored for about half of the rotation period. Accounting for the timing of carbon uptakes and greenhouse gas emissions is crucial for assessing wooden materials since it allows considering temporarily storing carbon and delaying GHG emissions (Levasseur et al., 2013). The Levasseur et al. method (2010) developed Dynamic Global Warming Potential characterization factors, providing a more accurate picture, particularly for temporary carbon storage and delayed emissions, as it includes the rotation period. Studying three different construction types (timber frame, concrete blockwork, and cast concrete) Fouquet et al. (2015) showed that differences between the timber house and the concrete houses were slightly smaller with traditional LCA than the ones obtained with the dynamic LCA approach.

To account for biogenic CO_2's impact before its sequestration by growing biomass, especially for long rotation species, Cherubini and colleagues developed the GWPbio index for different time horizons and biomass rotation periods (Cherubini et al., 2011). In fact, it has been demonstrated that different rotation periods strongly influence the capacity to remove carbon from the atmosphere by storage in buildings. The GWPbio index measures the impact of biogenic CO_2 emissions and can be combined with the standard IPCC method for measuring fossil GWP if the time horizon is the same. The longer the rotation period, the greater the mean stay of CO_2 in the atmosphere, resulting in a higher biogenic GWP. A negative GWPbio indicates that long-term storage has a more substantial positive impact than the emissions released at the end of life of the biogenic material, leading to a negative GWP. Longer storage periods and shorter rotation periods lead to more significant positive climate effects. In most LCA studies on building and construction, a time horizon of 100 years is generally assumed for the calculation of the GWP. However, in most standards, there is a distinction between temporary carbon storage (within a 100-year period) versus permanent carbon storage (more than 100 years) (Hoxha et al., 2020. Moreover, there is a significant difference between fast-growing, unconventional plant-fiber materials and wood. Straw is usually harvested annually, and fiber hemp can be ready to harvest as early as 70 to 90 days after seeding (Growing Hemp, 2016).

Finally, some results achieved by Pittau et al. (2022) for the city of Zurich through the simplified semi-static method with GWPBio index resulted very close to those obtained with a static -1/+1 approach, with a deviation between 4% min and 13% max. However, they observed that the dynamic LCA approach showed a significant deviation from the standard static approach, with a difference ranging from 34% minimum to 39% maximum. The study adopted the dynamic LCA model developed by Levasseur et al. (2010), with a specific focus on CO_2, N2O, CH4, and CO, which are the largest contributors to global warming impact (Pittau et al., 2022). In this case, they concluded that, although the importance of temporal factors and considerations in assessing the GWP of buildings that incorporate biogenic carbon is well established and demonstrated, a static approach using a range of -1 to +1 can yield reliable outcomes in a medium-term outlook. These results can aid environmental policies aimed at transitioning toward Zero-carbon cities (Pittau et al., 2022).

Table 1. Overview of approaches to biogenic carbon assessment and main documents

Approach	Biogenic carbon uptake	Biogenic carbon storage	Biogenic carbon release	Main document
0/0	CF= 0 CO_2e for CO_2	No temporary carbon storage. Credit (–1) for permanent carbon storage (>100 years)	CF= 0 CO_2e for CO_2	EC (2017a, 2017b)
-1/+1	CF= -1 CO_2e for CO_2	Impact may be documented separately	CF= +1 CO_2e for CO_2	EC (2013b) EN-15804 (2019) ISO-14067 (2018)
	CF= -1 CO_2e for CO_2 in the case of sustainable forest management, 0 otherwise		CF= +1 CO_2e for CO_2 in the case of sustainable forest management, 0 otherwise	ISO-21930 (2017) EN-16485 (2014)
	CF= -1 CO_2e for CO_2	weighting factor for delayed emissions may be calculated based on linear discounting. Carbon storage of >100 years considered as permanent carbon storage	CF= +1 CO_2e for CO_2	PAS 2050 (2011) ILCD (2010)
semi-static (GWP_{bio})	Biogenic global warming potential (GWP bio) considering the effect of forest regrowth and carbon storage			Cherubini et al.,2011 Guest et al., 2013
dynLCA method	Dynamic life-cycle analysis approaches with time-dependent characterization factors for all emissions (fossil and biogenic), allowing for the consideration of the effects of delayed emissions and carbon storage.			Daystar et al., 2017 De Rosa et al., 2018 Levasseur et al., 2013

5. Conclusions

In the LCA analysis, the literature on counting biogenic carbon credits suggests that a more detailed understanding of the time effects of storage, reabsorption, and time-shifted release is critical to ensure an accurate and reliable assessment of biogenic carbon credits. It focuses on understanding the amount of carbon stored and released from biogenic sources, such as forests, plantations, and crops. Biogenic carbon storage is influenced by multiple factors, including plant species, plantation age, climate, and management practices. The ability of a system to store carbon also depends on the rate of reabsorption of plants from the atmosphere.

This paper investigated different points of view on the topic, approaches, and techniques used to calculate carbon credits, identifying gaps in the existing literature, and taking into account some case studies and results. It emerges that, due to the methodological limits in LCA standards, carbon storage and end-of-life of bio-based products are not included in most LCA databases and validated Standards. Practitioners in Switzerland, for instance, frequently employ Ecoinvent and KBOB eco-BAU datasets to determine the carbon footprint of buildings. However, neither dataset provides information on biogenic carbon, which hinders building designers from obtaining a detailed estimate of carbon storage and potential delayed emissions (Pittau et al., 2022).

From the literature analyzed, three main alternative methods for biogenic carbon accounting were identified: the static (-1/+1) method, the temporal-depending (dynLCA) method, and the semi-static (GWPbio) method. From several studies' points of view, the standard -1/+1 method has limitations in observing the positive effect of delaying biogenic CO_2 emissions due to a non-time-dependent characterization factor adopted for a finite time horizon generally assumed equal to 100 years. On the other hand, the dynLCA method has proven to be robust and well-supported by data and scientific evidence in the literature in quantifying the disturbance to the climate due to a time-dependent pulse emission. However, many agree with its limitation to the implementation in standards and everyday practice due to the complexity of the calculation and the need for advanced knowledge in systems dynamic and dynamic modeling skills. Additionally, some temporal aspects, such as the time allocation of biogenic carbon uptake by forest growth and the rotation period of forests, are still controversial and increase uncertainties in the system, as they may be also dependent on economic and management factors, which is typically an unknown factor. The semi-static method has been identified by some studies as a simple and representative approach that considers temporal factors, such as storage and rotation periods, and is suitable for application to the building stock (Pittau et al., 2022).

Finally, it has to be underlined that the use of a single impact indicator is limiting in getting the full picture of the effects generated by materials. The LCA methodology relies on considering the entire life cycle and a range of indicators to avoid burden shifting. Evaluating materials by considering a single indicator risks steering the market on some products without taking into account all impact categories.

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